STANDARDS RESEARCH

In-Use Emissions Verification Testing for Diesel Engines in Underground Mining Operations

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Contents

Executive Summary

CanmetMINING performs emissions testing and certification of diesel engines according to the CSA M424 standards [1,2]. These standards are cited in various provincial legislation for underground mines in jurisdictions where a prescribed emissions-based ventilation rate is employed to ensure safe air quality for underground workers.

The CSA-prescribed ventilation rate is derived from engine emissions data obtained during a comprehensive laboratory certification test. This ventilation rate is then published and is available to underground mine operators for ventilation planning.

Once a new engine has been verified against a comprehensive exhaust emissions test, is approved and enters into service, there is no on-going verification program in place to monitor its in-use performance to ensure that emissions are not increasing and that the prescribed ventilation rate remains sufficient over time.

CanmetMINING proposed that a future version of the M424 family of standards should include an in-use verification component to ensure that emissions from certified diesel engines do not exceed the certification test values in service.

An in-mine field study was conducted in collaboration with Vale Canada to collect in-service engine emissions data for the purposes of developing an in-use verification program. The vehicle engine tested during this project was a CSA-verified engine and therefore the emissions were well known. In-use emissions were then measured from this engine for comparison with certification tests.

This trial comparison of in-use data with certification test data successfully demonstrated the feasibility of performing an in-use verification test on underground mining equipment, as well as the suitability of the test equipment and proper procedure.

It is recommended that this work be expanded to develop an in-use verification program for underground vehicles. This might include a study of in-use verification procedures in other jurisdictions, the collection of in-use emissions data from in-service vehicles underground, and a comparative laboratory study to review the suitability of transient test cycles for in-use verification.

"[A] prescribed ventilation rate will only provide sufficient protection for workers if the engine maintains its exhaust emissions quality at or close to certification test levels."

Introduction

Diesel engines are widely used in underground mining equipment for ore haulage, drilling, personnel transport and development/reclamation purposes. In most jurisdictions in Canada, the emissions and performance of these vehicles are governed by the CSA M424 standard [1,2].

The M424 standard mandates the use of a controlled laboratory engine emissions certification test to determine compliance. If the engine passes the emissions test, a ventilation rate sufficient to provide safe ambient air quality for workers is calculated and then prescribed for the engine when in operation underground.

The M424 engine certification test is performed on a single example of a new type of engine at the request of the manufacturer, and emissions data are collected from 18 to 22 modes selected from under the engine-operating curve (Figure 1). Figure 1 shows a typical engine operating curve (red), which relates the normalized engine speed to load under all operating conditions. The engine emissions are tested as a sample of these operating conditions, which are chosen based on the specific engine operating curve and expected vehicle duty cycle. An example of a typical certification ventilation rate is shown in Table 1.

This prescribed ventilation rate will only provide sufficient protection for workers if the engine maintains its exhaust emissions quality at or close to certification test levels. Maintenance faults, machine loading cycles, operator handling and unapproved control software may all affect the ability of the engine to maintain emissions quality.

At the present time, only the emissions from the engine certification test are used to determine compliance. There is no provision in the M424 standard to allow for verification of a certified engine in-use in an underground mine.

Figure 1 – *Typical engine operating curve (orange) with CSA M424 modal test points (blue).*

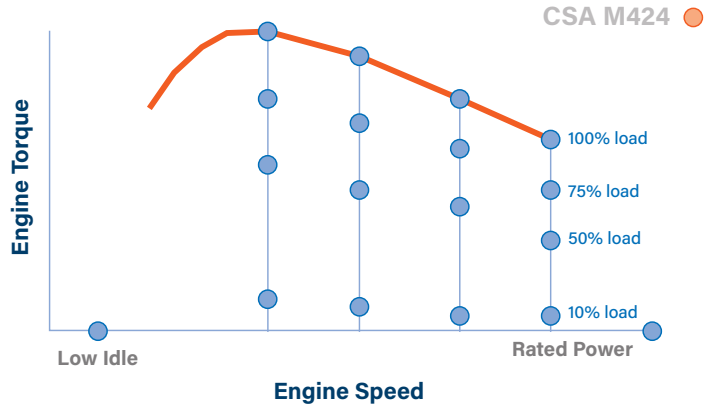


Table 1 – *Ventilation rates for a typical engine.*

GOVERNING STANDARD: CSA M424.2-90 (NON-GASSY MINES)				
Certificate Number	Engine Rating and Fuel Rate at Sea Level	Fuel Sulphur Fuel – ppm	Ventilation Prescription	
			CFM	m3/s
—	409 HP (305kW) @ 1800 RPM, 144.6 lb/h	500	20,700	9.77

The US Environmental Protection Agency (EPA) has developed an in-use verification program for heavy-duty on-highway vehicles [3]. This program is used to verify that engines are able to maintain certification levels of emissions while in use, with an allowance for deterioration and transient operation. The EPA specifies that the in-use emissions must not exceed 1.25 times the certification test emissions limit in a defined engine operation range known as the not-to-exceed (NTE) zone (Figure 2).

The NTE zone is bounded by a lower limit of 30% maximum power and 30% maximum torque. It is also bounded by an upper limit of 70% maximum power and 100% maximum torque. Carve-out areas, as specified in Figure 2, are excluded from the NTE control area as these regions represent operational conditions with greater emissions uncertainty.

In the EPA program, an engine is randomly selected for testing and, if it fails the NTE criteria, additional testing of other engines may be required. If the engines subsequently fail, a series of actions can be taken by the EPA, including revocation of the engine's emissions certificate.

The purpose of this project is to investigate the development of an in-use verification program for underground mining engines using the EPA method as a test model. If successful, this program may be incorporated into a future version of CSA M424.

Methods

Recently, an experimental trial was conducted on an underground mining vehicle at Vale's Copper Cliff North Mine (Sudbury, ON, Canada) [5]. The project consisted of two phases with a full description of the testing method and apparatus given in the Vale report [5].

Phase 1: Stationary (steady-state) emissions measurements were collected at three defined modes: low idle[1], high idle[2], full hydraulic stall[3], where emissions and engine control data were collected from a haulage truck in-service using an ECOM gas analyzer (ECOM EN, ECOM America, Ltd., Atlanta, GA).

Phase 2: Real-time emissions measurements were collected from a haulage truck during a typical vehicle duty cycle while in normal operations in-service using a SEMTECH-DS portable emissions measurement system (PEMS) (Sensors Inc., Saline, MI, USA) (Figure 3). This truck had been in service for 12,000 hours, representing approximately half its expected service life.

The truck was equipped with an engine that had been previously approved by CanmetMINING to the CSA M424 standard, therefore the certification emission levels were known. Emissions data collected included carbon dioxide (CO_2), carbon monoxide (CO), nitric oxide (NO), nitrogen dioxide (NO_2), and diesel particulate matter (DPM).

[1] low idle: the test engine is operated at 0% throttle, no load

[2] high idle: the test engine is operated at 100% throttle, no load

[3] full hydraulic stall: the test engine is operated at full throttle and loaded against the vehicle hydraulic system

Figure 2 – *EPA NTE control area for heavy-duty in-use verification test. Adapted from [4].*

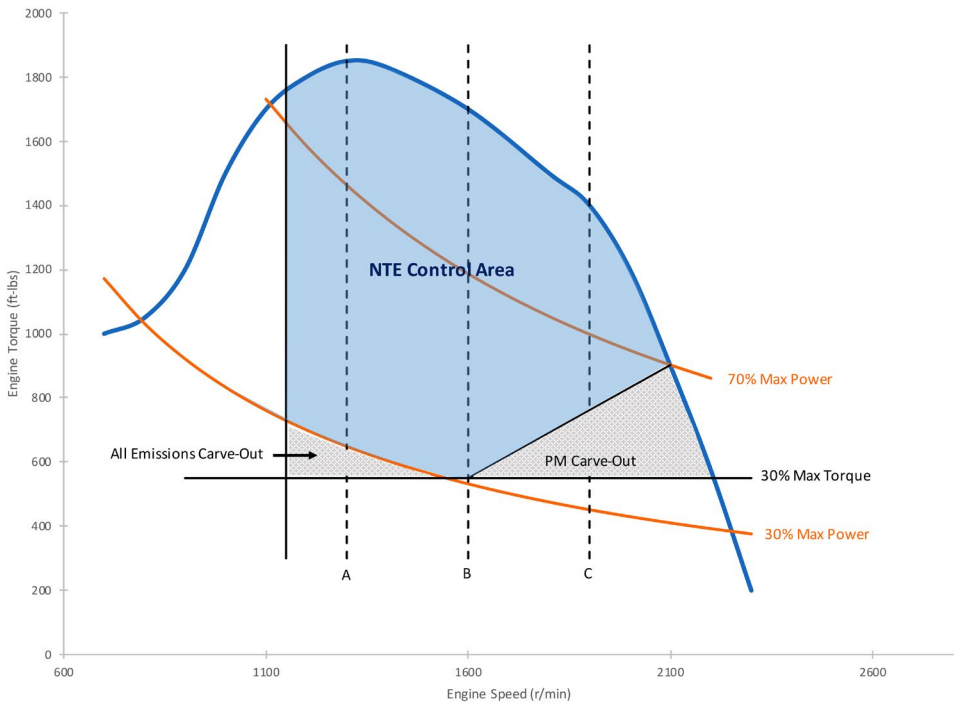


Figure 3 – *SEMTECH-DS in operation*

Phase 1 – Stationary (Steady-State) Testing

Prior to its use, the ECOM portable gas analyzer was set up and calibrated using calibration gases. The ECOM gas analyzer was used to measure CO, NO, and NO_2 tailpipe emissions in parts per million (ppm) and was used to perform a smoke dot test. All phase 1 testing was carried out in a garage above ground.

Emissions were measured at locations prior to any after-treatment to duplicate the original engine's certification test configuration. A series of stationary stall tests (low idle, high idle, and full hydraulic stall) were then performed on the surface using the ECOM gas sampler before and after the diesel particulate filter (DPF) to assess to engine emissions. A field trial (Phase 2) was then performed to assess the DPF performance including sampling of diesel particulate matter (DPM).

Phase 2 – Real-time Testing

The SEMTECH DS was used to measure the following emissions in parts per million (ppm): CO, NO, NO_2, and total hydrocarbon (THC) emissions. Emissions were measured in real time underground before any exhaust after-treatment to duplicate the original engine's certification test configuration. The instrument was installed on-board the vehicle and was operated in underground service for two days where eight individual work cycles were recorded.

Prior to use each day, the SEMTECH DS was calibrated using calibration gases, the DPM sampler was calibrated

using a calibrated flowmeter, and both instruments were installed onboard the test vehicle underground near the testing site.

At the test site, a series of short (approximately 1 hour) real-time gaseous emissions measurements were performed while the truck was in full operation during real mine duty cycles. Emissions were monitored in real-time from the vehicle using wireless transmission of the emissions data, provided there was a line-of-sight from the logging computer to the vehicle. Data-logged emissions were reviewed once after each test cycle and were repeated with adjustments, if required. Otherwise, the truck was returned to the staging area to complete the downloading of the data. After completion of testing, both the ECOM and SEMTECH DS were tested for sensor drift using calibration gases.

An algorithm was developed to analyze the raw emissions and engine control data, allowing emissions data to be extracted from the synchronized SEMTECH data at all points corresponding to certification test speeds (+/- 25rpm) and load points (+/- 5%). Emissions values within each of the eighteen the test speed and load point windows were then averaged. The average values were compared to the known engine's certification test values at each point.

Results

Phase 1 Emissions Results – Stationary (Steady-State) Testing

Engine-out emissions of CO, NO, and NO_2 were close to the average values measured during certification tests for the low idle, high idle and stall speed mode points. These modes were chosen because they are easily achieved in the field without complex instrumentation. In addition, low idle and high idle modes appear on the engine's certification test using the M424.1-16 and M424.2-16 standards. Stall speed is roughly equivalent to the rated power mode, which also occurs on the CSA test, thus allowing direct comparison of the field emissions data with the certification test data. The measured emissions were also reviewed against the EPA NTE criteria based on the original engine's certification test. All except two modes fell within the EPA NTE criteria of 1.25 (Table 2). Under a formal in-use test, the two exceedances would trigger an audit and review of the engine's certification test data, and perhaps an additional emissions test.

Table 2 – *Steady-state NTE criteria*

STEADY-STATE NTE FACTORS			
MODE	CO	NO	NO_2
Stall	0.60	1.20	0.44
Low Idle	0.73	1.17	1.28
Hi Idle	1.40	0.95	1.22

Phase 2 Emissions Results – Real-time Testing

The vehicle duty cycle from the in-use testing phase is shown in Figure 4.

The truck haul cycle is divided into sections to identify various phases:

A – Tramming empty on the level to ramp

B – Descending the ramp empty

C – Waiting at idle during ore loading process

D – Ascending the ramp

E – Tramming loaded ore to dump point

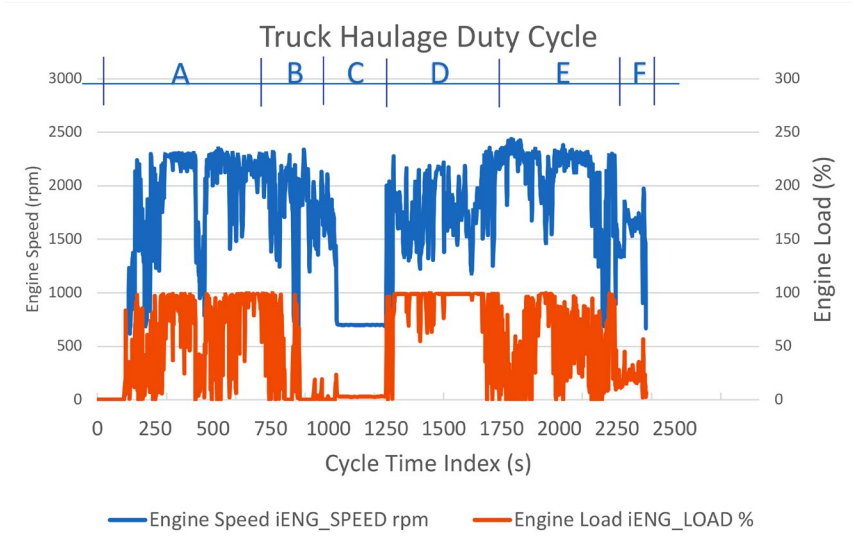
F – Dumping ore to crusher

Figure 4 demonstrates the changes in engine speed and engine load throughout the testing phases. For example, marked decreases in speed and load are evident in phase C while idling during the loading process, compared to other active phases of the testing period.

Not all the certification test modes were achieved during the in-use test (Table 3). Blue highlights signify that the test mode was achieved and captured during the test. No highlight means the test mode was not achieved during the test.

Where the test modes were achieved, the differences between certification emission values for carbon monoxide (CO) and the in-use emission values were calculated (Table 4). A result greater than 1.00 signifies that the in-use emissions value exceeded the

Figure 4 – *In-use transient duty cycle (engine speed and load) for testing truck*



certification value. A result greater than 1.25 indicates that it exceeded the certification value by 25% and would result in a failure of the NTE zone criteria.

Results less than or equal to 1.25 are highlighted in blue, signifying that the emissions at the test point passed the EPA NTE zone criteria. Values greater than 1.25 are highlighted in orange and indicate that the test point failed to meet the EPA NTE zone criteria.

Discussion

Based on the EPA NTE zone criteria, this engine would have failed the verification test. In jurisdictions that maintain an in-use verification program, this result may have several consequences:

- The failed result may trigger an audit of the engine's original certification documents and it may force a further in-use emissions test.
- If the second in-use test also fails the criteria, the engine manufacturer may be required to submit the engine for laboratory testing.
- If the engine fails this comprehensive test, its type approval certificate may be rescinded and the engine would no longer be legal for use.

However, it is important to note that there are a number of significant differences between the EPA NTE test and the CSA M424. First, the EPA certification test is transient, which may match its in-use transient test better than the M424 steady-state test. In addition, the NTE factor of 1.25 is based on a maximum family emissions limit value[4], which may be higher than the value achieved by the single engine during the certification test. The family emissions limit (FEL) is the maximum emissions limit measured during a type certification test. All engines within a specific design (family) must not exceed these limits. It allows the EPA to test one example of engine design and expand the certification to other sizes and ratings of engines within the same family.

These factors and others can have a significant effect on the performance of in-use emissions tests under the NTE factor limit. As underground mining applications are different from surface vehicles, more work is required to determine fair and appropriate NTE criteria for in-use testing of underground engines. For example, the effect

[4] EPA family emission limit: The maximum emission level established by a company for a test group, engine family or evaporative emission family.

Table 3 – *Test mode matrix of points achieved during in-use test.*

		SPEED (RPM)					
		1800	1600	1400	1200	700	2330
Load (%)	100	—	—	—	√	Idle	Idle
	75	√	√	√	—	—	—
	50	√	√	√	—	—	—
	10	√	√	√	√	—	—

Table 4 – *EPA NTE factors comparing in-use and certification emission test mode values for CO.*

		SPEED (RPM)					
		1800	1600	1400	1200	700	2330
Load (%)	100	—	—	—	4.3	2.18	0.88
	75	0.67	1	1.74	—	—	—
	50	4.05	2.5	0.94	—	—	—
	10	0.82	0.81	0.93	1.63	—	—

of ambient pressure and temperature can have a large effect on emissions for vehicles working in very deep mines and this will contribute to the vehicle's ability to achieve the NTE margin.

Conclusions

This project, conducted in conjunction with Vale Canada, has demonstrated the feasibility of performing an in-use verification test on underground mining equipment and the suitability of the test equipment and procedures. The work also identified some sources of potential error, such as the relationship between steady-state emissions test data values and "real-world" transient test data. It is recommended that further work be conducted to address gaps, which is required to develop an in-use verification program for underground vehicles. One suggestion is to develop a diesel engine transient test cycle for engine certification similar to the EPA Non-Road Transient Cycle (NRTC), and an assessment tool similar to the EPA NTE zone criteria, but suitable for mining. One possible solution might be to compare transient ventilation demand with prescribed engine ventilation rate to design mining NTE criteria.

It is anticipated that such a program would provide valuable information on engines operating in underground service, support future versions of the CSA M424 standard, and reassure the industry that adequate levels of protection of air quality are being maintained for workers underground.

Reference

1. *Flameproof non-rail-bound diesel-powered machines for use in gassy underground coal mines – Second Edition,* CSA M424.1-16, CSA Group, Toronto, 2016.

2. *Non-rail-bound diesel-powered machines for use in non-gassy underground mines – Second Edition,* CSA M424.2-16, CSA Group, 2016.

3. US EPA Office of Transportation and Air Quality, "In-Use Testing Program for Heavy-Duty Diesel Engines and Vehicles, Technical Support Document" *Document EPA420-R-05-006*, June, 2005.

4. Environmental Protection Agency. Title 40 Code of Federal Regulations. (2000 Oct 6). *Vol. 65 Fed. Reg. 59895, Control of Emissions of Air Pollution from 2004 and Later Model Year Heavy-Duty Highway Engines and Vehicles; Light-Duty On-Board Diagnostics Requirements, Revision; Final Rule.* Available: https://www.govinfo.gov/content/pkg/FR-2000-10-06/pdf/00-20144.pdf

5. CanmetMINING, "Vale / Mammoth Diesel Particulate Filter Evaluation" *CMIN WF_35906170*, Issued April, 2019.

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